A REVIEW OF GROUND COUPLED HEAT PUMP MODELS USED IN WHOLE-BUILDING COMPUTER SIMULATION PROGRAMS

Sung Lok Do
Research Assistant

Jeff S. Haberl
Professor

Energy Systems Laboratory
Department of Architecture
Texas A&M University
College Station, TX

ABSTRACT

Increasingly, building owners are turning to ground source heat pump (GSHP) systems to improve energy efficiency. Ground-coupled heat pump (GCHP) systems with a vertical closed ground loop heat exchanger are one of the more widely used systems. Over the last thirty years, a number of simulation models have been developed to calculate the performance of the ground heat exchanger (GHX). The several computer programs can evaluate the GCHP systems as a part of the whole-building energy simulation.

This paper briefly presents a general introduction to GSHP systems and the GCHP system, and reviews the currently developed GCHP models and compares computer programs for a GCHP design. In addition, GHX models which play an important role on the GCHP performance are reviewed. Finally, several widely recognized computer simulation programs for building energy analysis are compared regarding their GCHP simulation capability.

INTRODUCTION

Ground source heat pumps (GSHP) are systems that have received considerable attention in the recent decades. The GSHP system utilizes relatively constant ground temperatures instead of ambient temperatures for residential and commercial space heat pump applications. Running a compressor in the GSHP system requires a reduced amount of electricity input since the ground temperatures provide a more efficient heat source/sink for the heating and cooling cycle when compared to ambient temperature.

The GSHP is the general term that includes the ground coupled heat pump (GCHP), groundwater (GWHP), and surface water (SWHP) heat pump. Although each of these systems utilizes the ground as a heat source/sink, they vary in the different ways the ground temperatures are delivered to the heat pump.

The GCHP system has closed loop GHXs that circulate a fluid through tubes in contact with the ground. GWHP has opened loop GHXs that circulate fluid extracted from wells in the ground or from lakes or bodies of water. SWHP has closed loop or opened loop GHXs. The selection of the best GSHP is largely dependent on the local, geological and thermal characteristics of the soil at a site. Figure 1 shows conceptual schematics of different GSHP systems.

In general, growing interest is focused on the GCHP system that use closed loop for the ground heat exchanger systems over systems that use to an open loop. The major reason for the shift toward GCHPs is that the technology can be applied anywhere. On the other hand, the other systems (i.e., GWHP and SWHP) may not be applicable to all sites. If all of them can be applied, the GWHP system is the most energy efficient and cost effective when ample ground water is available on a site. Similarly, SWHP system can be used when lakes or ponds are nearby.

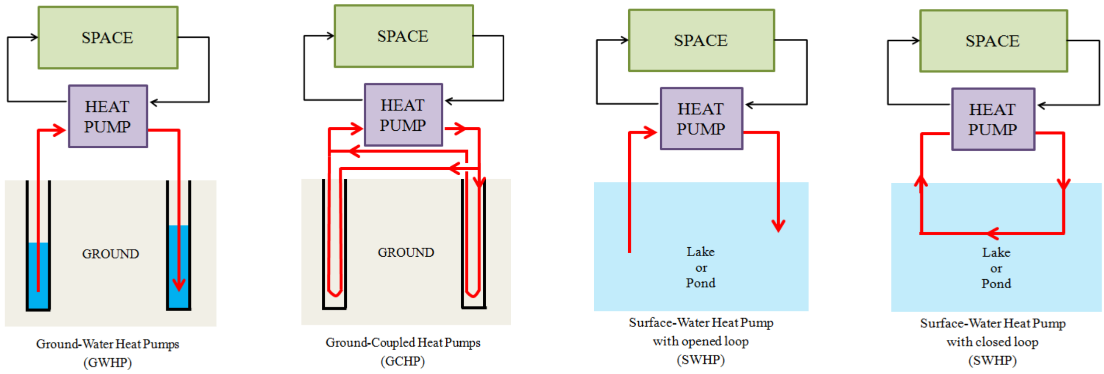

Figure 1. Schematics of different ground source heat pumps

The GCHP system has two types of closed loop ground heat exchangers (GHXs); a vertical closed loop and a horizontal closed loop. In residential use, the vertical closed loop GHX is used more commonly than the horizontal loop GHX due to the reduced area required.

In spite of their popularity, GCHPs have a high initial cost, limitations in GCHP design and installation infrastructure, and lack of new technologies to improve GCHP system performance. In addition, the design of GCHP systems has been slower than expected due to the lack of reliable, easy-to-use simulation tools for GCHP systems (Liu & Hellström, 2006). In response to this concern, the Oak Ridge National Laboratory (ORNL) has been working to develop new tools for analysis and evaluation of GCHP systems (Hughes, 2008).

Currently, there are a number of simulation models that have been developed to calculate the performance of the GHXs. Several computer programs have ever been developed to simulate the GCHP system for whole-building energy simulation programs. This paper reviews the currently developed GHX models and compares computer programs for GCHP design/simulation.

OVERVIEW OF GCHP AND GSHP SYSTEMS

Ground source heat pumps (GSHPs) utilize ground as a heat source or sink to provide space heating, cooling, and domestic hot water (ASHRAE 2003). GSHP systems are generally more efficient than conventional HVAC systems because ground temperatures (between about 5 and 30°C) are generally much closer to room conditions than the ambient dry or wet bulb temperatures over the whole year. As the result, world wide applications of GSHPs have been growing at an annual rate of 10% over the past ten years (Rybach, 2005). Most of this growth has occurred in the United States and Europe. In the USA alone, over 50,000 GSHPs are sold each year, with a majority of these for residential application. It is estimated that one half million units are installed, with 85% of the system being closed-loop earth connection (46% vertical well, 38% horizontal trenches) and 15% of the system use open loop GHX systems (Lund et al., 2004).

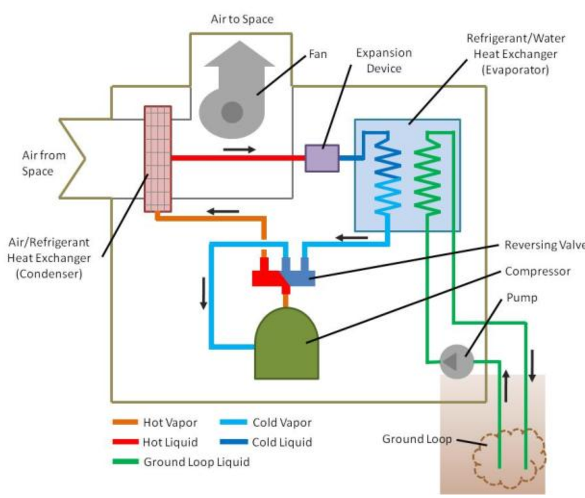

Figure 2. Sketch of the GCHP in the heating cycle

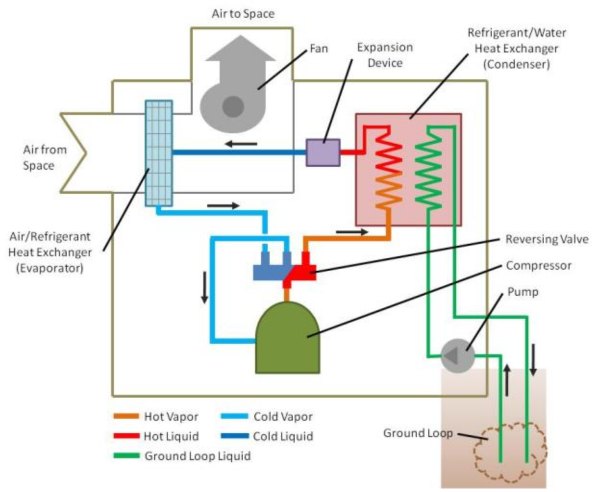

Figure 3. Sketch of the GCHP in the cooling cycle

GCHP systems, which are often called closed-loop or earth-coupled ground source heat pump systems, were first pioneered in the 1960s by Swedish engineers. And, in the 1970s, mathematical models for the GCHP technology were developed and tested by Dr. Jim Bose and Dr. Harry Braud (Wagers & Wagers, 1985). In a similar fashion as the GSHP, the GCHP takes an advantage of the ground as heat source and sink. In addition, the GCHP system has the advantage that the entire system can be located inside a house with only two added pipes connecting the HP to the GXH. This feature gives a life expectancy of 20 years due the reduced wear and tear the system experiences. Compared with air source heat pump (ASHP) which is usually used for residential houses, the ASHP system has a life expectancy of only 10 to 20 years (Golish, 1994).

The GCHP is generally classified according to two types of GHX designs: vertical and horizontal. Vertical GHXs are normally more efficient than horizontal GHXs and require less piping since the ground temperature in a vertical well is steadier than in a horizontal trench for a year. However, closed loop GHXs with a vertical well are generally more expensive than closed loop GHXs with a horizontal trench (CANMET, 2005).

The vertical GHXs consist of two, small-diameter HDPE tubes that are placed in a vertical borehole that is subsequently filled with a solid medium. The HDPE tubes are thermally fused at the end that is inserted into the bottom of the bore to form a return U-bend. Vertical tubes range from 0.75 to 1.5 in. in diameter. Bore depths rage from 50 to 600 ft, depending on local soil conditions and available drilling equipment. To reduce thermal interference between individual bores, a minimum borehole separation distance of 20 ft is recommended when loops are place in a grid pattern (ASHRAE, 2007). After the HDPE pipe is inserted, the hole is grouted and the connecting trench back-filled. The grout prevents the surface water from draining into the borehole and contaminating the groundwater, and also prevents one borehole from leaking into an adjacent borehole. Following grouting and backfilling, the vertical pipes are connected to horizontal underground supply and return header pipes. The header pipes that connect to and from the heat pump are used to carry the GHX heat transfer fluid from the vertical pipes to the heat pump (CANMET, 2005). Once all the boreholes are connected to the header pipes, the trench is then filled.

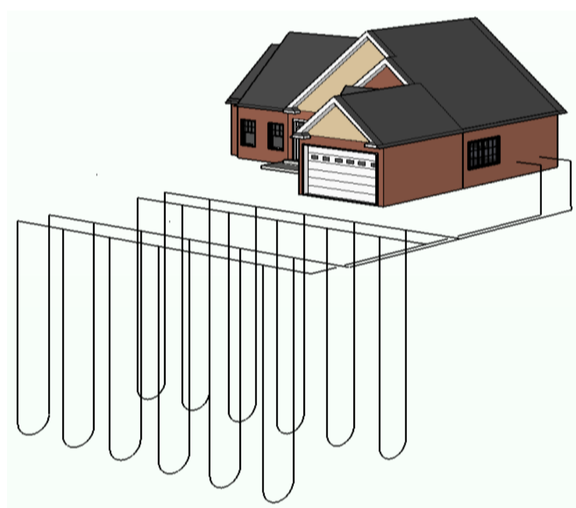
Figure 4. Sketch of the vertical GHX

Horizontal GHXs are generally suitable for smaller applications such as residential and light commercial buildings since a larger land area is required. The piping in a horizontal GHX can be buried relatively near the ground surface and still benefit from the moderating temperatures that the earth provides. Ground temperatures may fluctuate as much as ±10˚F at a depth of 6 ft, which can fall below freezing temperatures. Therefore, an antifreeze solution must be used in most heating-dominated regions (ASHRAE, 2007).

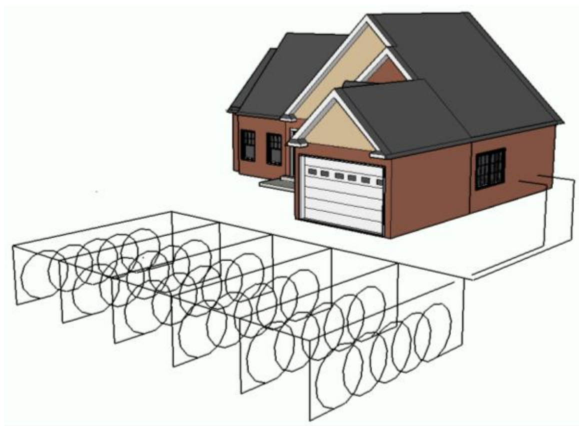

Figure 5. Sketch of the horizontal GHX

REVIEW OF VERTICAL GHX MODELS

To design a GCHP or GSHP system, ground heat exchanger model is used to calculate the return water temperature from the GHX to the heat pump. The return water temperature depends on the properties, depth and length of the ground loops, the time-of-year, the operation hours, and the ground thermal properties. The size of the GHX influences the return temperature, which plays an important role in the heat pump's performance. Therefore, the main objective of the GHX simulation model is GHX properties to determine the return water temperatures gives a known building load, and surrounding ground temperatures.

The GHX simulation model usually has two separate parts for the heat transfer analysis. One is outside the borehole and the other is inside the borehole. The analysis outside the borehole must account for the heat transfer through the surrounding medium (i.e., soil, rock, sand). The wall temperature inside the borehole is then determined by the analysis outside the borehole. The analysis inside the borehole must account for the heat transfer through the grout, and HDPE pipe into the fluid. This analysis generally considers thermal properties and resistance of materials such as grout, U-tube pipes, and fluid.

A number of simulation models for the heat transfer outside the borehole have been developed; most of these models were based on either an analytical or a numerical methodology. Two analytical models are generally used for the design for the GHX: one is Kelvin's line source model and the other is a cylinder source model. Most of the GHX models used in simulation programs are based on one of these two analytical methodologies. Different simulation models have been developed. They use analytical or numerical solution to simulate the thermal behavior of the GHX. Table 1 shows the different approaches to simulate the GHX.

Table 1. Analytical and numerical solution for GHX models

Solution Approach	GHX Simulation Models	References
Analytical Solution	Kelvin's Line Source Theory	Kelvin (1882), Ingersoll et al. (1948)
	Cylinder Source Solution	Carslaw and Jaeger (1947)
Numerical Solution	Eskilson's Model	Eskilson (1987)
	Hellström's Model	Hellström (1989)
	Mei and Emerson's Model	Mei & Emerson (1985)
	Muraya's Model	Muraya et al. (1996)
	Rottmayer, Beckman, and Mitchell's Model	Rottmayer et al. (1997)
	Shonder and Beck's Model	Shonder & Beck (1999)

Numerical models offer a high degree of flexibility with acceptable accuracy compared with the analytical models. However, most of the numerical models use polar or cylindrical grids, which can be computationally inefficient due to the large number of complex grids used in a real system. In addition, numerical models can be inconvenient to incorporate directly into a whole-building energy analysis program (Yang et al., 2010).

Analytical models are usually based on a number of assumptions, which are simplified in order to solve the complicated mathematical algorithms. For example, the assumption of a line source at the center of the borehole neglects the physical size of U-tube in the borehole. Therefore, the accuracy of analytical results is slightly reduced than the numerical models. However, the required computation time of analytical models is usually much less than the time required for numerical models. In addition, the straightforward, simplified algorithm used in the analytical models can be readily integrated into a whole-building, energy design simulation program (Yang et al., 2010).

Analytical solution

The line source model is a classic solution that calculates the temperature distribution around an imaginary line. The model assumes that the borehole is a line source. The earliest application of this approach was developed by Lord Kelvin to calculate the thermal performance through ground heat exchanger pipes. Hence, this model is also called "Kelvin's line source theory". In this model, the soil or ground is assumed as an infinite medium with a uniform and constant initial temperature. Ingersoll and Plass (1948) used this model to ground loop heat exchangers. This method neglects the heat transfer in the direction of the borehole axis. In addition, this method assumes that the heat flux across the ground surface and down the bottom of the borehole does not occur. Therefore, the heat conduction process in the ground is simplified as one-dimensional one. This approach has been widely utilized in analytical design methods. A number of improvements for this approach have been proposed to account for some complicated factors and to enhance the accuracy in estimation of the GHX (Yang et al., 2010). For example, one major improvement to this method by Hart and Couvillion (1986) utilized the line source model to estimate continuous time-dependent heat transfer between a line source and the ground. They introduced the far-field radius (r_∞), which considered the amount of heat transfer from the line source to the ground. Table 2 shows the history to develop the line source approach.

Table 2. Brief development history for the line source approach

Year	Line Source Approach
1882	Lord Kelvin Kelvin's line source model
1948	Ingersoll and Plass Modified line source model
1986	Hart and Couvillion Enhanced line source model

In another development, Carslaw and Jaeger (1947) developed the cylindrical source model which treats the two legs of the U-tube as a single pipe that is co-axial with the borehole. Ingersoll et al. (1954) modified this model to size buried heat exchangers. Then, Kavanaugh (1985) refined the model to determine the temperature distribution or the heat transfer rate around a buried pipe. ASHRAE (2007) procedure uses the cylinder source model developed by Kavanaugh. Table 3 shows the history to develop the cylindrical source approach.

Table 3. Brief development history for the cylindrical source approach

Year	Cylinder Source Approach
1947	Carslaw and Jaeger Cylinder source model
1954	Ingersoll et al. Modified cylinder source model
1985	Kavanaugh Modified cylinder source model

Unfortunately, both the one-dimensional model using Kelvin's theory and the cylindrical source model developed by Kavanaugh neglect the axial heat flow along the borehole depth: therefore they can be inadequate for analyzing the long-term operation of the GCHP systems (Yang et al., 2010).

Numerical solution

A number of numerical models have been developed to calculate the temperature distribution around U-tube boreholes. These numerical models have been developed to examine the nature of heat transfer around borehole heat exchangers for research purposes. In addition, the models have been used in system simulations to evaluate field data. Whereas both line source models and cylindrical models using analytical solutions neglect the axial heat transfer in the direction of the borehole axis, numerical solutions can account for the axial heat transfer by considering a borehole with finite length. In a number of the numerical GHX models that have been developed, two numerical approaches are the most common: the g-function model developed by Eskilson (Eskilson, 1987) and the other is the duct storage (DST) model developed by Hellström (Hellström, 1989).

Table 4. Brief development history for the numerical solutions

Year	Numerical Approach
1985	Mei and Emerson
1987	Eskilson
1989	Hellström
1996	Breger et al.
	Muraya et al.
1997	Rottmayer et al.
	Thornton et al.
1999	Shonder and Beck
	Yavuzturk and Spitler
2003	Zeng et al.

In Eskilson's model, a two-dimensional numerical calculation was used for a single borehole in homogeneous ground with constant initial and boundary temperature. The thermal capacitance of the borehole elements, such as the pipe wall and the grout, are neglected. The concept of the g-function was introduced by Eskilson to explain the dimensionless temperature response factors at the borehole wall. Eskilson's g-function calculates the temperature change at the borehole wall in response to a stepped heat input for a unit time. The disadvantage of this approach, however, is that it is time-consuming, and it can hardly be incorporated directly into an hourly, whole-building design and energy analysis program for practical applications. This is because the g-functions of the GHXs with different configurations have to be pre-computed and stored as a massive database (Yang et al., 2010). In addition, the g-function model developed by Eskilson does not explain the thermal resistance effects of the borehole elements, such as the pipe wall, the grout, and the fluid flow. Yavuzturk & Spitler (1999) enhanced Eskilson's g-function algorithm to account for the effects of the thermal properties of the grouting material and the thermal properties of the anti-freeze on the GHX heat transfer performance. The enhanced g-function model by Yavuzturk & Spitler is called the short time-step model.

Hellström (1989) developed a simulation model for vertical ground heat storage which uses densely packed ground loop heat exchangers for seasonal thermal energy storage (Yang et al., 2010). In Hellström's model, a duct ground heat storage system (DST) is defined as a system where heat is stored directly in the ground. A duct or channel system is used to exchange the heat between a heat carrier fluid which is circulated through the duct and the storage region. The thermal process in the storage region deals with three separate problems: the global heat flow problem, the local thermal problem, and steady-flux problem. The global heat flow problem describes the interaction between the storage volume and the surrounding ground called as far-field. The local thermal problem presents the thermal process around the individual ducts (the boreholes). The steady-flux problem explains heat pulses around a pipe for a constant injection or extraction rate. The DST model implemented in TRNSYS relies on an analytical solution for the steady-flux process and a numerical method for the global and local processes to model the ground heat exchanger.

COMPUTER SIMULATION PROGRAMS FOR WHOLE-BUILDING ENERGY ANALYSIS

In building energy research, hourly whole-building computer simulation programs are widely and extensively used for analyzing and evaluating complex building performance to improve energy efficiency. The U.S. Department of Energy (DOE) currently provides information on 389 building software tools for evaluating energy efficiency, renewable energy, and sustainability in buildings. Of the 389 tools, five simulation programs are the most widely recognized tools related to whole-building energy simulation: the DOE-2.1e program, eQUEST, EnergyPlus, TRNSYS, and EnergyGauge USA.

Three computer simulation programs (the DOE-2.1e program, eQUEST, EnergyPlus) have used by a number of individuals and organizations since those programs can simulate most of the building features in building energy analysis. Of five tools, four simulation tools except of the DOE-2.1e program have the capability to simulate the GCHP system. The DOE-2.1e program, EnergyPlus, and TRNSYS support complete documents to users, including description for the system functions. The TRNSYS is a transient simulation program with a modular structure to solve complex energy system problems by breaking the problem down into a series of smaller components. The EnergyGauge USA is divided two seperate simulation tools: residential use and commercial use. This tool is also possible for easy and fast evaluation on whole-building energy simulation but unavailable for multiple-conditioned zones and room-by-room HVAC sizing. Table 5 shows the summary for features of the five simulation tools most widely used.

Table 5. Summary for features of five representative simulation tools

Computer Simulation Programs	GCHP Model	Complete Document	Whole-Building Energy Simulation	Availability to Recompile Source Code	Acceptable Run Time
DOE-2.1e	x	o	o	o	o
eQUEST	o	x	o	x	o
EnergyPlus	o	o	o	o	x
TRNSYS	o	o	x	o	o
EnergyGauge USA	o (Residential only)	x	o	x	o

o : Yes
x : No

<u>Computer simulation programs with GCHP model</u>

The current DOE-2.1e program (version 136) does not have the capability to simulate the GCHP system. However, the previous DOE-2.1e program (version 110) had the capability of the GCHP simulation. Liu and Hellström (2006) mentioned the DOE-2.1e is the first computer program that integrated GCHP simulation into a whole-building energy simulation program.

Currently, four widely used simulation programs have the capability to simulation GCHP systems: eQUEST, EnergyPlus, TRNSYS, and EnergyGauge USA. However, not all of these programs have published documentation about the detailed algorithms. In addition, only two programs of these four tools allow users to customize the source code. The EnergyGauge USA program evaluates the GCHP system performance for residential use only.

The eQUEST/DOE-2.2 program simulates the performance of a GCHP system at a particular hour using a modified water source heat pump system simulation module. The DOE-2.2 is the simulation engine of eQUEST. The eQUEST/DOE-2.2 program uses an enhanced g-function algorithm, which was proposed by Eskilson (1987) at Lund University, Sweden, for fast calculation of the borehole wall temperature. The enhanced g-function model use the procedures developed by Yavuzturk & Spitler (1999). Liu & Hellström (2006) presented the verification and validation results of the enhanced GHX model implemented into the eQUEST/DOE-2.2 and integrated a dedicated interface into the eQUEST Graphical User Interfacd (GUI) for GCHP simulations.

The EnergyPlus program uses the models for the water source heat pump with a ground loop heat exchanger in the whole-building GCHP annual energy simulation. The water-to-water heat pump model was developed by Jin & Spitler (2002). This program also uses the short time step G-function model developed by the Yavuzturk & Spitler (1999) as the ground heat exchanger model. The operation of this model was verified by comparing results to analytical values (Fisher & Rees, 2005).

TRNSYS calculates water source heat pump performance with a ground heat exchanger for its GCHP system. This simulation program uses the DST model by (Hellström, 1989) as the ground loop heat exchanger. Thornton et al. (1997) used Hellström's approach as a part of a detailed component-based simulation model which was implemented in TRNSYS (Klein et al., 1996). The model was calibrated to monitored data from a family housing unit by adjusting input parameters such as the far-field temperature and the ground formation thermal properties (Yavuzturk, 1988).

Table 6 shows a summary of the computer simulation tools with the GCHP simulation modules. Most of the programs use a water source heat pump with a GHX unit. To calculate the GHX performance, the g-function method is mostly used, with the exception of the TRNSYS program, which uses the DST model.

Table 6. Summary of the computer simulation programs with the GCHP function

Simulation Programs	GCHP Function	HP Model	GHX Model
DOE-2	No (Version 136)	-	-
	Yes (Version 110)	Water source HP	g-function
eQUEST	Yes	Water source HP	g-function
EnergyPlus	Yes	Water source HP	g-function
TRNSYS	Yes	Water source HP	DST
EnergyGauge USA	Yes (Residential use only)	Geothermal HP	-

Other programs for GCHP design/simulation

Other programs which solely focus on GCHP system design have been developed. Yang et al. (2010) introduced several GCHP design tools based on the line-source model and cylindrical source model. These tools utilize an analytical approach to calculate GCHP system performance. Using the line-source model, the computer programs are the Lund program, the EED program, GLHEPRO, and the GeoStar program. The computer program using a cylindrical source model is the GchpCalc.

The Lund program (Claesson & Eskilson, 1988, Claesson et al., 1990, Claesson 1991, and Hellström, 1991) for sizing vertical GHXs uses algorithms based on the Eskilson's approach (Eskilson, 1987). The Earth Energy Designer (EED) was developed to be a more user-friendly program version of the Lund program (Sanner & Hellström, 1996). The GLHEPRO program (Spitler, 2000) is developed primarily to design vertical GHXs used in commercial or institutional buildings, using Eskilson's approach. The GeoStar program was developed by a research group in China (Cui, et al. 2007). The GHX heat transfer models in the software consist of two parts: one for outside the borehole through the solid soil/rock and the other for inside the borehole.

Finally, the GchpCalc program using a cylindrical source model helps engineers in the design of vertical GCHP systems. The detailed concepts of this program can be found in Kavanaugh & Rafferty (1997), The method is based on the solution of the cylindrical source model. This method has been used widely within the United States for design of the GCHP systems (Kavanaugh & Rafferty, 1997).

CONCLUSION

The use of GSHP, in high performance building is becoming a popular option for building system designers. The models of GSHP systems applied to buildings have been developed. Of the models developed, the closed loop GCHP model is the most widely used. The GCHP models focus on a GHX model to calculate its performance. The GHX models use an analytical, numerical, or a combined approach to solve the heat transfer between the borehole and surrounding ground.

Five whole-building simulation programs (i.e., the DOE-2.1e program, eQUEST, EnergyPlus, TRNSYS, and EnergyGauge USA) are reviewed in this paper. Four programs except of the DOE-2.1e program have the capability to simulation GCHP systems. However, none of them had well documented models, which could easily model complex building shapes with acceptable run times. Hence, there is a need to develop such a model.

REFERENCES

ASHRAE 2007. ASHRAE Handbook-HVAC Applications: Geothermal Energy. *American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.* (pp. 32.1 - 32.29). Atlanta: ASHRAE.

Breger, D., Hubbell, J., Hasnaoui, H., & Sunderland, J. 1996. Thermal energy storage in the ground: comparative analysis of heat transfer modeling using U-tubes and boreholes. *Solar Energy* 56(6), (pp. 493-503).

CANMET 2005. *CLEAN ENERGY PROJECT ANALYSIS: RETScreen Engineering & CASES TEXTBOOK.* Ottawa, Canada: Natural Resources Canada.

Carslaw, H., & Jaeger, J. 1947. *Heat Conduction in Solids.* Oxford: Claremore Press.

Claesson, J. 1991. PC design model for thermally interacting deep ground heat exchangers. *Proceeding WS on GSHP Montreal,* HPC-WR-8, (pp. 95-104). Sittard.

Claesson, J., & Eskilson, P. 1988. PC design model for heat exchanger boreholes. *Proceeding. 4th International Conference Energy Storage JIGASTOCK 88,* (pp. 135-137). Paris.

Claesson, J., Eskilson, P., & Hellström, G. 1990. PC design model for heat extraction boreholes. *Proceeding 3rd WS on SAHPGCS Göteborg, CIT; 1990:3*, (pp. 99-102).

Cui, P., & H. Yang, Z. F. (2007). The simulation model and design optimization of ground source heat pump systems. *HKIE Transactions, 14(1)*, (pp. 1-5).

DOE 2010. *EnergyPlus Energy Simulation Software*. Retrieved July 2010, from Energy Efficiency & Renewable Energy: http://apps1.eere.energy.gov/buildings/energyplus/

Eskilson, P. 1987. *Thermal analysis of heat extraction boreholes.* Lund, Sweden: Doctoral thesis, University of Lund, Dept. of Mathmatics.

Fisher, D., & Rees, S. 2005. Modeling ground source heat pump systems in a building energy simulation program (EnergyPlus). *Ninth International IBPSA Conference.* Montreal, Canada: Building Simulation.

Hart, D., & Couvillion, R. 1986. *Earth Coupled Heat Transfer.* Publication of the National Water Well Association.

Hellström, G. 1989. *Duct ground heat storage model: Manual for computer code.* Lund, Sweden: University of Lund.

Hellström, G. 1991. PC-Modelle zur Erdsondenauslegung. *IZW Bericht* 3/91, (pp. 229-238).

Ingersoll, L., & Plass, H. 1948. Theory of the Ground Pipe Heat Source for the Heat Pump. *ASHVE Transactions* 54, (pp. 119-122).

Ingersoll, L., Zobel, O., & Ingersoll, A. 1954. *Heat Conduction with engineering, geological, and other applications.* New York: McGraw-Hill.

Jin, H., & Spitler, J. 2002. A parameter estimation based model of water-to-water heat pumps for use in energy calculation programs. *ASHRAE Transactions* 102(1) (pp. 3-17). ASHRAE.

Kavanaugh, S. 1985. *Simulation and experimental verification of vertical ground-coupled heat pump systems. Ph.D. dissertation.* Stillwater, OK: Oklahoma State University.

Kavanaugh, S., & Rafferty, K. 1997. *Ground-source heat pumps, design of geothermal systems for commercial and institutional buildings.* Atlanta: ASHRAE.

Kelvin, W. 1882. *Mathematical and Physical Papers, Vol. 1.* Cambridge University Press.

Liu, X., & Hellström, G. 2006. Enhancements of an integrated simulation tool for ground-source heat pump system design and energy analysis. *Proceedings of Ecostock 2006, the 10th International Conference on Thermal Energy Storage.* The Richard Stockton College of New Jersey.

McLain, H., & Martin, M. 1999. A preliminary evaluation of the DOE-2.1E ground vertical well model using Maxey school measured data. *ASHRAE Transactions* 105(2). ASHRAE.

Mei, V., & Emerson, C. 1985. New approach for analysis of ground-coil design for applied heat pump systems. *ASHRAE Transactions* 91(2) (pp. 1216-1224). ASHRAE.

Mogensen, P. 1983. Fluid to Duct Wall Heat Transfer in Duct System Heat Storages. *Proceedings of the International Conference on Subsurface Heat Storage in Theory and Practice.* Swedich Council for Building Research.

Muraya, N., O'Neal, D., & Heffington, W. 1996. Thermal interference of adjacent legs in a vertical U-tube heat exchanger for a ground-coupled heat pump. *ASHRAE Transactions* 102(2), (pp. 12-21).

Omer, A. (2006). Ground-source heat pumps systems and applications. *Renewable and Sustainable Energy Reviews* .

Rottmayer, S., Beckman, W., & Mitchell, J. 1997. Simulation of a single vertical U-tube ground heat exchanger in an infinite medium. *ASHRAE Transactions* 103(2) (pp. 651-659). ASHRAE.

Sanner, B., & Hellström, G. (1996). "Earth Energy Designer", eine software zur Berechnung von Erdwärmesondenanlagen. *Proceeding 4. Geothermische Fachtagung Konstanz, GtV,* (pp. 326-333).

Shonder, J., & Beck, J. 1999. Determining effective soil temperature thermal properites from field data using parameter estimation technique. *ASHRAE Transactions* 105(1) (pp. 458-466). ASHRAE.

Spitler, J.D. 2000. GLHEPRO -- A design tool for commercial building ground loop heat exchangers. *Proceedings of the Fourth International Heat Pump in Cold Climates Conference*. Aylmer, Quëbec.

Thornton, J., McDowell, T., Shonder, J., & P.J. Hughes, D. P. 1997. Residential Vertical Geothermal Heat Pump System Models: Calibration to Data. *ASHRAE Transactions* 103(2) (pp. 660-674). ASHRAE.

Wagers, H., & Wagers, M. 1985. The earth-coupled or geothermal heat pump air conditioning system. *Proceedings of the Second Symposium on Improving Building Systems in Hot and Humid Climates*. College Station, TX.

Yang, H., Cui, P., & Fang, Z. 2010. Vertical-borehole ground-coupled heat pumps: A review of models and systems. *Applied Energy* , 16-17.

Yavuzturk, C. 1988. *Modeling of vertical ground loop heat exchangers for ground source heat pump systems.* Stillwater, OK: Oklahoma State University.

Yavuzturk, C., & Spitler, J. 1999. A short time step response factor model for vertical ground loop heat exchangers. *ASHRAE Transactions,* 105(2) (pp. 475-485). ASHRAE.

Zeng, H., Diao, N., & Fang, Z. 2003. Heat transfer analysis of boreholes in vertical ground heat exchangers. *International Journal of Heat and Mass Trasnfer* , 4467-4481.